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SECTION I

INTRODUCTION AND PROJECT GOALS

This report describes the goals, the progress to date in two areas of effort, and the plans for future work on Contract NObsr 91332. The four major goals on this project are listed below. The first two are of primary importance since the latter two cannot be fully achieved without reaching the first two.

The development of refined methods of "automated LOFAR-gram reading" is an improvement to the PACT techniques of extracting spectral clues from a received signal. It is now intended that the implementation of these techniques be primarily by a general-purpose digital computer. This approach will allow greater freedom in the choice of processing techniques, will avoid the problems of interconnecting the existing equipment to a new type of computer, and will permit a more thorough investigation to be carried out within the available funds.

Development of practical methods of predicting (computing) important spectral characteristics of passive sonar signals from a knowledge of the generating ship's (target's) engineering and operating configuration.

More specifically, this problem is approached by developing generic models of certain vibratory ship's components. Integral to the task of developing prediction methods are the subtasks of collecting the two types of data required—tape recordings of ship-generated acoustic signals and engineering data on the corresponding ships.

Development of a classification algorithm which operates on the spectral clues extracted by the LOFAR-gram reader, obtaining a set of probable ship design characteristics, and thence a set of probable target classifications.

Implement the procedures developed above in a manner suitable for use in further studies and for test and evaluation of these techniques.

SECTION II

SIGNAL PROCESSING STUDIES

This section describes a study of spectrum analysis in passive sonar classification, including the results obtained to date.

2.1 BACKGROUND AND REASONS FOR THE STUDY

Passive sonar signal processing has traditionally made extensive use of spectrum analysis for detection and classification purposes. Spectrum analysis techniques will be used extensively by Automatic Passive Sonar Target Classification (APSTAC) and will be combined in a later study with transient processing to provide a complete classification methodology.

Current plans call for APSTAC signal processing to be performed on a general-purpose digital computer (using analog-to-digital conversion and digital tape storage of the signals). One of the key factors making this approach possible was the recent development of the Fast Fourier Transform (FFT)[1] which dramatically reduces the time and thus the cost of computer spectrum analysis. The FFT is a computational algorithm which reduces the number of time consuming operations required in transforming a set of equispaced data points.

The study described in this progress report was performed to generate a definite base for the analysis of real passive sonar signal recordings, and consisted of:

a. Generation of the required computer programs

b. Checkout of these programs

c. Familiarization with the properties of these programs through simple examples

d. Investigation of the methodologies of computer spectrum analysis

e. Investigation of proposed methods of signal processing using computer simulations of passive sonar or derived signals

f. Investigation of the effects of quantization and sampling rate on the effectiveness of the signal processing

NOTE: This study provided an opportunity for gaining further insight into the influence of the FFT on general computing methods.

2.2 COMPUTER METHODS OF SPECTRUM ANALYSIS

Digital computers may be used to perform spectrum analyses of time waveforms by each of several different approaches. Until recently, the accepted method was to compute the appropriate auto- or cross-correlation function (mean-lagged product) for delays less than some fraction of the total analyzed data length, and then to compute a fraction of the Fourier coefficients of the correlation function. This method yielded only a small fraction of the available spectral information, and was thus time consuming and costly.

A series of recent papers[1, 2, 3] has described a new algorithm for computing Fourier coefficients which is dramatically faster, for practical-sized problems, than the algorithms used previously. As a result the most efficient method of computing spectral data is now to Fourier transform the entire data sequence to be analyzed, compute the squared magnitudes of the Fourier coefficients, and perform smoothing, if appropriate. In addition, the FFT also now provides the fastest method to compute correlations or convolutions.[4] Except for overhead functions, the time required by the FFT to compute a set of T Fourier coefficients is proportional to T log T whereas the computation times for the algorithms used previously were proportional to T^2.

A digital computer operates on signals which have been quantized in both amplitude and time. An independent theoretical study is now under way at Litton to determine the effect on the degree of accuracy in amplitude quantization with respect to the fidelity of the spectra obtained. Results of this other study will be incorporated into APSTAC as soon as they become available.

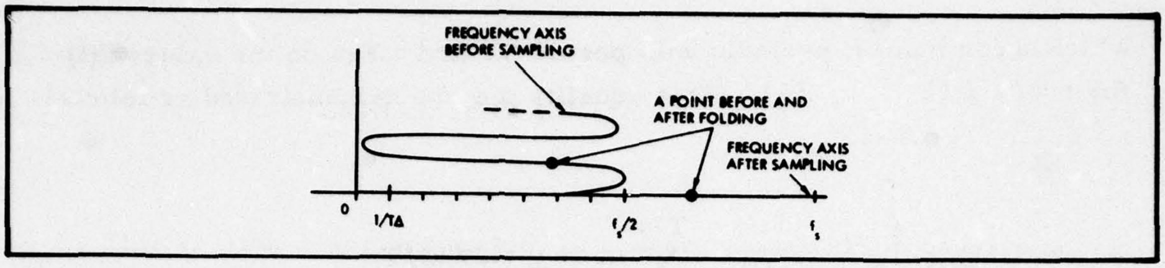


Figure 2-1. Frequency Axis Folding to Produce Aliasing 1734-11

The effect of time sampling on the computed spectrum may be described as shown in Figure 2-1 and is termed aliasing. The power which is at the frequency $nf_s \pm f$, where $f_s = 1/\Delta$ is the sampling rate and n is an integer, cannot be distinguished from power at frequency f. Thus, the transformation of the continuous frequency spectrum to the discrete frequency spectrum may be thought of as a folding operation as shown in Figure 2-1 followed by sampling in frequency. (It should be noted that $f_s/2$ is often called the folding frequency.) Thus, the sampling error in estimating spectra depends upon the rate at which the spectrum falls off with increasing frequency. If, for example, the highest frequency of interest, B, is $f_s/4$ and the spectrum falls off at a rate of 6dB per octave, then the aliasing power will be about 9dB below the desired power level.

The FFT operates on a finite sequence of complex data, x(t) for t = 0, 1, 2, ..., T-1,* and yields the finite, discrete Fourier transform, $X\left(\frac{k}{T}\right)$, of the time sequence as:

$$X\left(\frac{k}{T}\right) = \frac{1}{T}\sum_{t=0}^{T-1} x(t)e^{-i2\pi kt/T}, \quad \text{for } k = 0, 1, 2, \ldots, T-1$$

The inverse transform of $X\left(\frac{k}{T}\right)$ is:

$$\tilde{x}(t) = \sum_{k=0}^{T-1} X\left(\frac{k}{T}\right)e^{i2\pi kt/T}$$

*Throughout most of this section the time variable t has been normalized to an integer. Real time will then be tΔ, where Δ is the sampling interval.

which is continuous, periodic with period T, and takes on the values $\tilde{x}(t) = x(t)$ for $t = 0, 1, 2, \ldots, T-1$. This equality may be demonstrated as follows. For $t = 0, 1, \ldots, T-1$,

$$x(t) - \tilde{x}(t) = x(t) - \sum_{k=0}^{T-1} X\left(\frac{k}{T}\right) e^{i2\pi kt/T}$$

$$= x(t) - \sum_{k=0}^{T-1} e^{i2\pi kt/T} \frac{1}{T} \sum_{\nu=0}^{T-1} x(\nu) e^{-i2\pi k\nu/T}$$

$$= x(t) - \sum_{\nu=0}^{T-1} x(\nu) \frac{1}{T} \sum_{k=0}^{T-1} e^{i2\pi k(t-\nu)/T}$$

$$= x(t) - x(t) = 0$$

where the orthogonality condition:

$$\sum_{t=0}^{T-1} e^{i2\pi(m-k)t/T} = \begin{cases} T \text{ if } k = m \\ 0 \text{ if } k \neq m \end{cases}$$

has been used.

To show that the complex exponential is orthogonal over a finite set of equispaced points, note that:

$$\sum_{t=0}^{T-1} e^{i2\pi t\ell/T} = \sum_{t=1}^{T} e^{i2\pi t\ell/T} \text{ for } 1 \leq \ell \leq T-1$$

so that the sum of the first forward differences of:

$$e\left(\frac{t\ell}{T}\right) = e^{i2\pi t\ell/T}$$

is zero. That is,

$$\sum_{t=0}^{T-1}\left[e\left(\frac{(t+1)\ell}{T}\right) - e\,\frac{t\ell}{T}\right] = \sum_{t=0}^{T-1} e\left(\frac{t\ell}{T}\right)\left[e\left(\frac{\ell}{T}\right) - 1\right]$$

$$= \left[e^{i2\pi\ell/T} - 1\right]\sum_{t=0}^{T-1} e^{i2\pi t\ell/T}$$

$$= 0 \text{ for } 1 \leq \ell \leq T-1$$

Thus, the summed product of complex exponentials is zero unless the arguments are the same. That is,

$$\sum_{t=0}^{T-1} e^{i2\pi \ell t/T} = 0 \text{ if } \ell \neq 0 \pmod{T}$$

The other theorems which are conventionally stated for continuous time and frequency variables also carry over to the discrete, finite sample point case. For example, Parseval's theorem holds; the sum of the powers at each frequency is equal to the total power in the time series. That is,

$$\sum_{k=0}^{T-1} \left| X\left(\frac{k}{T}\right) \right|^2 = \sum_{k=0}^{T-1} \frac{1}{T^2} \sum_{t,\ \ell=0}^{T-1} x(t)\, x^*(\ell)\, e^{i2\pi k(\ell - t)/T}$$

$$= \frac{1}{T} \sum_{t=0}^{T-1} \left| x(t) \right|^2,$$

where an asterisk is used to denote complex conjugation.

The finite, discrete Fourier coefficients have several important properties. The coefficients are periodic with period T.

$$X\left(\frac{k+T}{T}\right) = \frac{1}{T} \sum_{t=0}^{T-1} x(t)\, e^{-i2\pi t(k+T)/T} = X\left(\frac{k}{T}\right)$$

Therefore, the coefficients for $k = \frac{T}{2} + 1, \frac{T}{2} + 2, \ldots, T-1$ are those that are normally associated with negative frequencies.

Let $a_k = X\left(\frac{k}{T}\right)$ for simplicity of notation. If x(t) is real, $a_k{}^* = a_{-k}$ and so,

$$a_k + a_{-k} = a_k + a_{T-k} = 2\mathrm{Re} \left| a_k \right|$$

Because of the periodicity of the sequence $\left| a_k \right|$, if x(t) is real and T is even,

$$x(t) = \sum_{k=0}^{T-1} a_k\, e^{i2\pi kT/T}$$

$$= a_o + \left(a_1\, e^{i2\pi t/T} + a_{T-1}\, e^{i2\pi t/T}\right) + \ldots + a_{T/2}\, e^{i2\pi \frac{tT/2}{T}}$$

$$x(t) = a_o + 2\text{Re}\left\{a_1\right\} \cos \frac{2\pi t}{T} + 2\text{Re}\left\{a_2\right\} \cos \frac{4\pi t}{T} + \ldots$$

$$+ 2\text{Re}\left\{a_{T/2-1}\right\} \cos \frac{2\pi t\,(T/2 - 1)}{T} + (-1)^t\, a_{T/2}$$

Similarly, if x(t) is imaginary and T is even,

$$x(t) = a_o + 2 \sum_{\ell=1}^{T/2-1} \text{Im}\left\{a_\ell\right\} \cos \frac{2\pi \ell t}{T} + (-1)^t\, a_{T/2}$$

Convolution in the time domain corresponds to the dual operation in the frequency domain if the convolution is performed "circularly;" i.e., as if the time sequences were periodic:

$$\sum_{t=0}^{T-1} x(t)\, y(t - \tau) = \frac{1}{T} \sum_{k=0}^{T-1} X\left(\frac{k}{T}\right) Y\left(\frac{k}{T}\right) e^{i2\pi\, kt/T}$$

Now that some of the more important properties of the finite discrete Fourier transform have been summarized, it remains to be decided as to how the Fourier coefficients are to be used in computing a "power spectral density" or "spectrum." The theory and practice of spectrum computation and/or estimation are undergoing continual development. The general subject is one of considerable complexity because of the many facets which must be considered. The method to be used in any particular case should be chosen with regard to the specific conditions and objectives of that case.

If one is computing a spectrum of a time function which is characterized by a stable, strong line structure it is usually important to minimize the "leakage" of power at a frequency $f \neq k/T$ for any integer k; i.e., f is not any of the sampled frequencies, over to the spectral estimates at frequencies removed from f. The most widely accepted way of reducing leakage is to "hann" the

data, either by multiplying the time series by $[1 - \cos 2\pi t/T]$ (a cosine bell), or by convolving the Fourier coefficients with the three element sequence -1/2, 1, -1/2. Hanning the data by either method changes the power leakage from a $|f - k/T|^{-2}$ dependence to a $|f - k/T|^{-6}$ law.[2, 5]

If the time waveform to be spectrum analyzed is random with a fairly flat spectrum, one is faced with the necessity of trading off some frequency resolution for increased statistical stability of the estimated spectrum. This can be achieved by locally smoothing the Fourier coefficients by convolving with a suitably chosen short sequence.

The simplest type of spectrum which can be computed from the Fourier coefficients, $X(k/T)$, is the (unmodified) periodogram, $P(k/T)$, given by:

$$P(k/T) = |X(k/T)|^2$$

This is a natural definition for a spectrum, but one which has drawbacks in many cases.[6] The operations of hanning and smoothing of the Fourier coefficients as described above result in modified periodograms. For the purposes of this study to date, however, the spectrum computed has been the unmodified periodogram.

2.3 SIMULATION OF PASSIVE SONAR SIGNALS

During the course of the APSTAC study, a number of different methods, involving spectrum analysis, of processing passive sonar signals will be studied both theoretically and experimentally. In order to test these methods of signal processing under completely known conditions with controlled degrees of variability, several programs have been written which generate time series simulating the properties of passive sonar signals which are currently of interest; i.e., harmonic groups in a noise background. The programs have been written in a general manner so that input parameters such as the number of harmonic groups, the fundamental frequencies, the amount of phase drift of each harmonic group, the amplitudes of the individual harmonics, etc., can be specified with ease.

In addition a simple noise generation routine has been prepared which can serve as the background noise for the harmonic groups, or as a signal source for studying the effects of sampling rate. The routine written is basically a one-pole, low-pass filtering operation on the output of a normal or gaussian random number generator (white noise). In continuous time, such a filter has an impulse response:

$$h(t) = \sqrt{2\alpha}\, e^{-\alpha t}\, U_1(t)$$

where $U_1(t)$ is a unit step at $t = 0$ and α is a parameter which specifies the filter effective smoothing time,

$$H(f) = \sqrt{\frac{2}{\alpha}} \left(1 + i\,\frac{2\pi f}{\alpha}\right)^{-1}$$

and has an asymptotic falloff of 6dB per octave.

The digital equivalents of the above continuous functions are:

$$h_1(t) = \sqrt{1 - e^{-2\alpha}}\; e^{-\alpha t}\; \delta_1(t)\, U_1(t)$$

and

$$H_1(f) = \frac{1}{\alpha}\sqrt{1 - e^{-2\alpha}} \left(1 + i\,\frac{2\pi f}{\alpha}\right)^{-1} * \delta_1(f)$$

where $\delta_a(t)$ is a periodic unit impulse train with period a, and * denotes convolution. This form of the transfer function indicates that the one-pole characteristic, $(1 + i\ 2\pi f/\alpha)^{-1}$, is repeated at unit intervals along the frequency axis, and thus graphically indicates the restrictions on α to avoid aliasing.

The half-power bandwidth of the one-pole filter is $B_1 = \alpha/2\pi$ and for an nth order cascade is $B_n = B_1 \sqrt{2^{1/n} - 1}$. Therefore, $n = 2$, $B_2 = 0.643B_1$ and for $n = 3$, $B_3 = 0.51B_1$.

The actual implementation of this filter on a computer is recursive in form. That is, if r(t), t = 0, 1, . . . is the input sequence, a new sequence is formed by

$$\rho(t) = r(t) + e^{-\alpha} \rho(t-1)$$

and this is then scaled by $A = \sqrt{1 - e^{-2\alpha}}$ to retain unity power transfer.

If the input to this filter r(t), is a sequence of zero mean, independent random numbers (white noise), with variance σ_r^2 then the autocovariance function of the output, $\tilde{r}(t)$, is

$$C_{\tilde{r},\tilde{r}}(t, t-\tau) = \mathbb{E}\left\{\tilde{r}(t)\tilde{r}(t-\tau)\right\}$$

$$= \mathbb{E}\left\{A\sum_{\ell=0}^{t} r(\ell)e^{-(t-\ell)\alpha} \; A\sum_{m=0}^{t-\tau} r(m)e^{-(t-\tau-m)\alpha}\right\}$$

$$= \sigma_r^2 e^{-\alpha\tau}\left[1 - (e^{-2\alpha})^{t-\tau+1}\right]$$

The bracketed term displays the effect of the starting transient on the filter output. After the filter "fills up," however, the output may be said to possess a correlation function (dependent only upon the shift variable τ), i.e.,

$$R_{\tilde{r},\tilde{r}}(t) = \lim_{t\to\infty} C_{\tilde{r},\tilde{r}}(t, t-\tau) = \sigma_r^2 e^{-\alpha\tau}$$

Hence, the filter must be initialized by several iterations before the output is added as background to the simulated harmonic group structures.

The first signal generation subroutine to be described here, SIGGEN 2 (SIGGEN 2 is a generalization of an earlier subroutine called SIGGEN 1), is intended to simulate a direct passive sonar signal by a sum of harmonic groups plus a background noise. Up to three harmonic groups can be generated and each group has a specific set of parameters:

$$F_j, A_j, n_j, A_{j1}, A_{j2}, \ldots, A_{jn_j}$$

where $n_j \leq 11$. The form of the jth harmonic group is

$$s_j(t) = \sum_{n=1}^{n_j} A_{jn} \sin\left[n\left(2\pi \frac{F_j}{T} t + \varphi_j(t)\right) + \theta_{jn}\right]$$

where θ_{jn} is a uniform $[0, 2\pi]$ random number, independent over both j and n. T values of $s_j(t)$ are generated in a block as an input to the spectrum analysis routine. Each harmonic group has its own independent random phase drift, $\varphi_j(t)$ which is generated by

$$\varphi_j(t) = \begin{cases} 0 \text{ if } t=0 \\ \lambda_j \psi_j(t) + \varphi_j(t-1) \quad \text{for } t > 0 \end{cases}$$

where $\psi_j(t)$ is a sequence of random numbers independent over both t and j and uniform $[-a_j, a_j]$, with $a_j = (3F_j/T)^{1/2}$. This choice of a_j results in an rms phase drift of λ_j radians per cycle. The output of this routine can, at option, be quantized into a specified number of levels. Examples of spectra of signals generated by this routine will be given in the next subsection.

A subroutine, SIGGEN 3, has been written which produces an output similar to that observed when a passive sonar signal is spectrum analyzed. The spectrum is read out serially, in time, and the spectrum as a time function is one-bit quantized on a dynamic threshold which is just above the continuous portion of the spectrum. This series of operations is illustrated in Figure 2-2. Such a binary signal may be used for detecting the harmonic groups and other line structure properties of a passive sonar signal. (Just such a signal was used as the input to the PACT correlator.)

The output of SIGGEN 3 is a binary sequence which is a sum of signal terms simulating the effect of harmonic groups in the hypothetical input passive sonar signal, and a noise term which simulates the effect of noise spikes

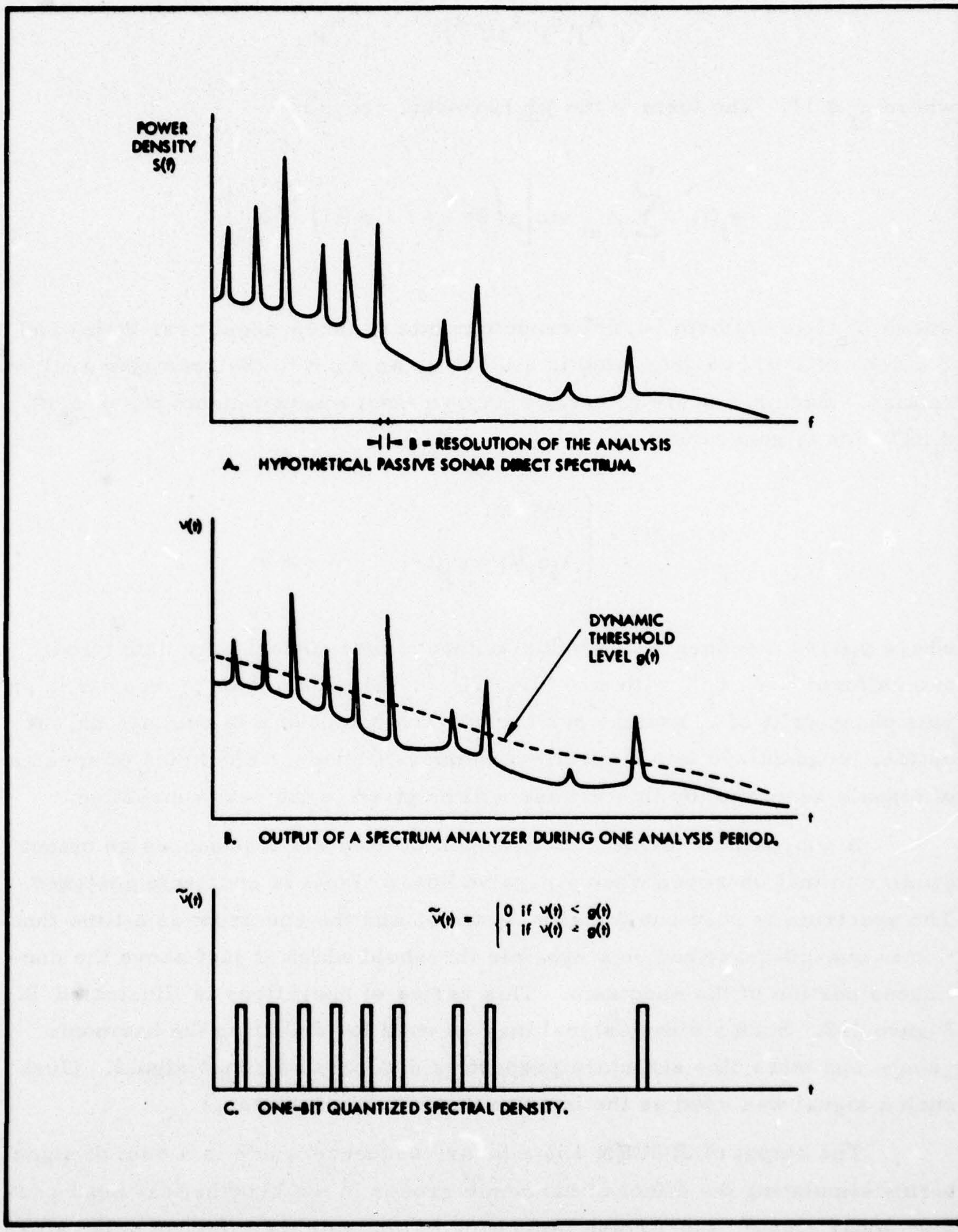


Figure 2-2. Generation of Representative Spectral Line Structure

1734-12

in the continuous portion of the "input spectrum" exceeding the one-bit quantization threshold. The probability of an "input noise spike" exceeding the one-bit quantization threshold is assumed to be constant over the entire system bandwidth so that the probability of a noise pulse in the simulation output is

$$n(t) = \begin{cases} 0 \text{ with probability } 1 - \beta \\ 1 \text{ with probability } \beta \end{cases}$$

for $t = 0, 1, 2, \ldots, T - 1$. β is an input parameter to the program.

The signal components in the SIGGEN 3 output consist of roughly periodic, binary pulse trains, where the probability of pulse occurrence decays exponentially with increasing time (time corresponds to frequency in the sonar spectrum). Let the interval

$$I_{jm} = \left[m\left(D_j - \frac{d_j}{2}\right),\ m\left(D_j + \frac{d_j}{2}\right)\right]$$

The form of an individual signal component is then

$$s_j(t) = \begin{cases} 0 \text{ if } t \notin I_{jm} \\ 0 \text{ with probability } 1 - P_j e^{-\alpha_j m} & \text{if } t \in I_{jm} \\ 1 \text{ with probability } P_j e^{-\alpha_j m} & \text{if } t \in I_{jm} \end{cases}$$

for $t = 0, 1, \ldots, T - 1$, and $m = 1, 2, \ldots [(T - 1)/(D_j + d_j/2)]$.

There can be up to three signal terms and for each there is an input parameter array

$$D_j,\ d_j,\ P_j,\ \alpha_j$$

The output binary sequence is generated from the signal and noise terms by the summing operation

$$x(t) = \begin{cases} 0 \text{ if } y(t) = \sum_{j=1}^{ISR} s_j(t) + n(t) = 0 \\ 1 \text{ if } y(t) \geq 1 \end{cases}$$

where ISR is the number of signal terms. Examples of spectra of signals generated by SIGGEN 3 will be given in the next subsection.

The SIGGEN subroutines are combined with a fast Fourier transform subroutine, called FFT, and an output subroutine, called OUTPP, to make up the functional portions of a general software package called the Frequency Domain Processing Program (FDPP). The general operations of the FDPP are diagrammed in Figure 2-3. This program has been written in FORTRAN and used on an IBM 360/50 computer.

2.4 EXAMPLES OF SPECTRA OF SIMULATED SIGNALS

In order to illustrate the properties of the finite discrete Fourier transform, a special computer run was made using SIGGEN 1. The time function which was spectrum analyzed was

$$\xi(t) = \frac{1}{\sqrt{2}} e^{-i2\pi \frac{70}{512} t} + \cos 2\pi \frac{80}{512} t + \cos 2\pi \frac{150.5}{512} t$$

$$+ \cos 2\pi \frac{300.25}{512} t + \cos 2\pi \frac{511.5}{512} t$$

for $t = 0, 1, 2, \ldots, T = 512$, which includes a complex term and four real terms. The complex time function has a spectral component only at $f_1 = -70/512$ whereas a sine or cosine of the same frequency would have spectral components at $\pm f_1$. Two of the terms in $\xi(t)$ are at frequencies of the form $f = n/T$ where n is an integer. These frequencies are among those sampled by the finite,

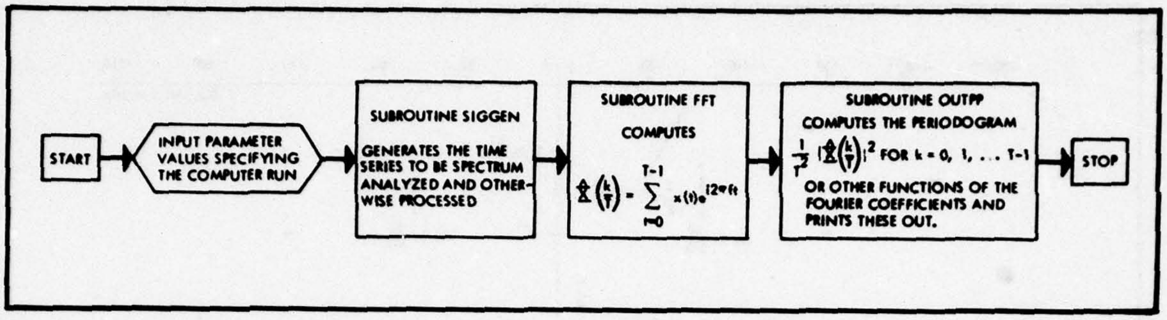


Figure 2-3. Frequency Domain Processing Program Flow Chart — 1734-13

discrete Fourier transform and these terms do not affect the values of the other spectral components (with the exception of computational roundoff). (This is due to the orthogonality of the complex exponentials, or sines and cosines, over a finite, equispaced set of points.)

In contrast to the effect of terms at frequencies of the form $f = n/T$ where n is an integer, terms at frequencies of the form $f = \lambda/T$ where λ is not an integer, affect the values of every spectral component. Naturally, terms in $\xi(t)$ at frequencies of the form $f = \lambda/T$ contribute most strongly near their own frequencies and their effect on other spectral components falls off rapidly with $|k - \lambda|/T$ in a manner dependent upon how close λ is to an integer. All these effects are shown in Figure 2-4 which is a plot of the periodogram of $\xi(t)$.*

$\xi(t)$ contains two terms at frequencies above the Nyquist rate,** namely at the frequencies 300.25/512 and 511.5/512. A term in $\xi(t)$ above the Nyquist frequency shows up at (or around) its low frequency aliase, in this case 1 - (300.25/512) = (211.75/512) and (0.5/512), respectively. Therefore, the

*All the spectra presented here have been simplified to an extent. The spectra are functions of a discrete variable k, but portions of them have been plotted as if they were continuous. Furthermore, the spectra to follow have been smoothed (visually) over the low power density portions.

**Since time has been normalized to the integers, the Nyquist rate here is 1/2.

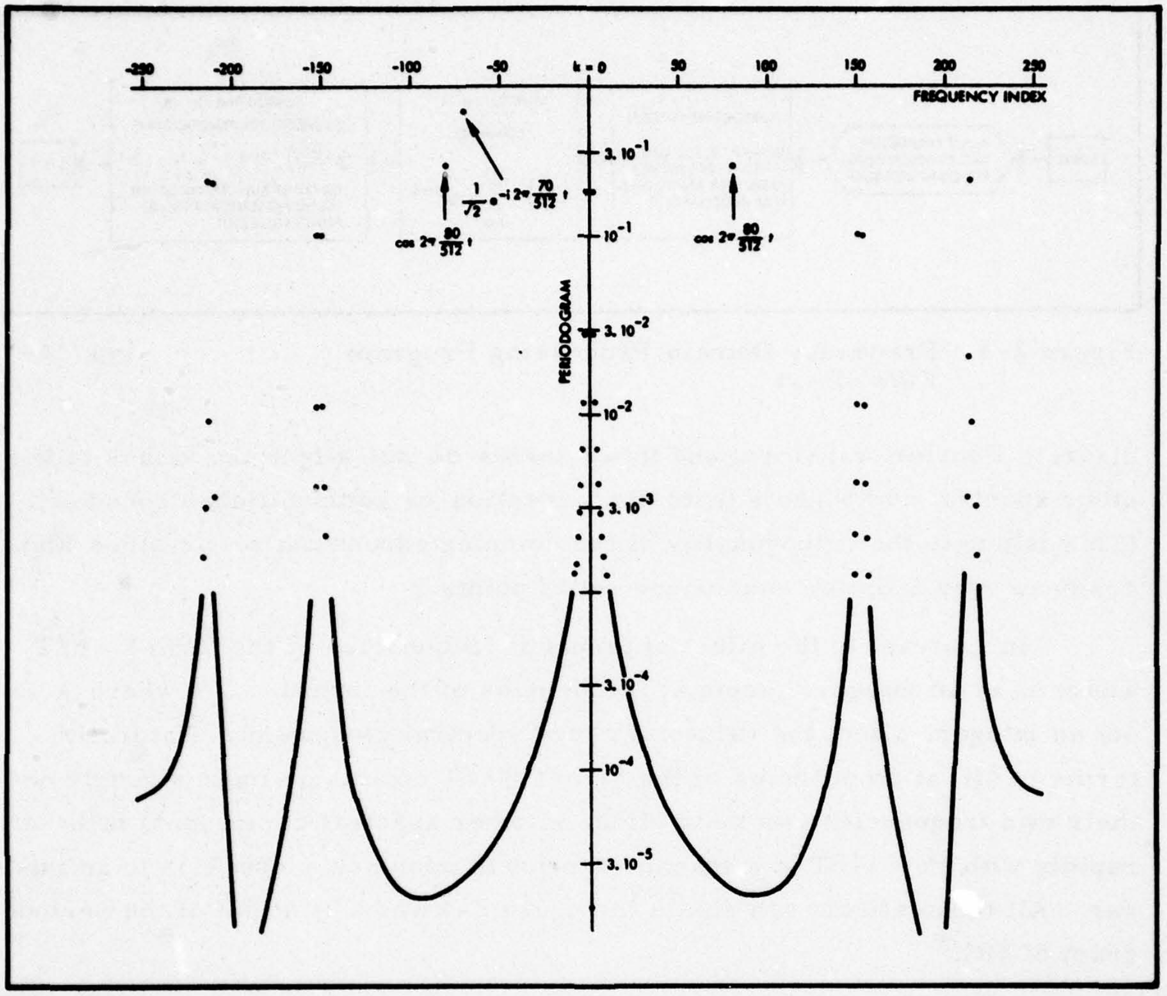


Figure 2-4. Spectrum of Five (Complex) Sine Waves 1734-14

spectral components shown at k = ±211.75 and at k = ±0.5 in Figure 2-4 show the effect of undersampling, i.e., sampling at less than twice the frequency of terms in the time function which have significant power. Note that the zero frequency term is not strongly aliased by cos $2\pi(511.5/512)t$, rather, the value shown at k = 0 is primarily due to the term in $\xi(t)$ with frequency 150.5/512. Computational roundoff error is negligible in all of the described runs.

As described in the previous subsection, the subroutine SIGGEN 2 generates signals which are harmonic groups with random phase drifts. Figure 2-5 shows a (smoothed) spectrum of such a signal. The analyzed time

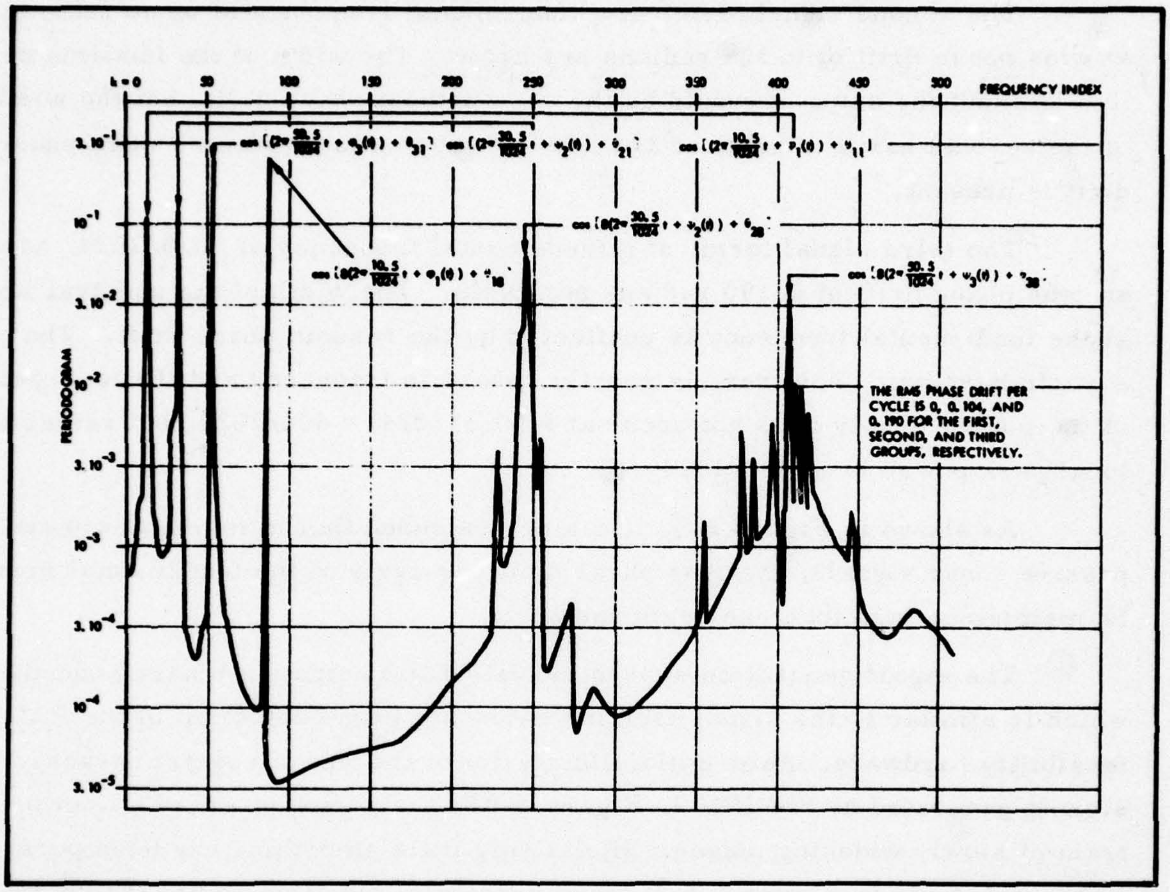


Figure 2-5. Spectrum of Three Harmonic Groups with Random Phase Shift 1734-15

function consists of the sum of three signal groups, each of which consists of a cosine at the fundamental frequency of the group plus a cosine at the seventh harmonic of the group fundamental. There is no noise background to these harmonic groups.

The first signal term, at the fundamental frequency 10.5/1024, has no random phase drift and so its spectral line widths are essentially the same as similar lines in Figure 2-4. The seventh harmonic is 84/1024, a sampled frequency, and so the harmonic line is narrower than the fundamental spectral line.

The second signal term, at a fundamental frequency of 30.5/1024, has an rms phase drift of 0.104 radians per cycle. The width of the fundamental line is about the same as would be the case without phase drift, but the width of the seventh harmonic line at 244/1024 is substantially greater when phase drift is present.

The third signal term, at a fundamental frequency of 50.5/1024, has an rms phase drift of 0.190 radians per cycle. The width of the spectral line at the fundamental frequency is unaffected by the random phase drift. The seventh harmonic, however, is greatly spread in frequency and the local peak of the power density does not occur at 8(50.5/1024) = 404/1024, but rather the local peak power is at 408/1024.

As shown in Figure 2-5, it can be concluded that in terms of simulating passive sonar signals, the rms phase drift per cycle of the fundamental must be maintained less than one-tenth radian.

The signal generation subroutine SIGGEN 3 outputs a binary sequence which is similar to the signal used for harmonic group detection in the PACT feasibility hardware. As an initial illustration of the type of spectra possessed by signals generated by SIGGEN 3, Figure 2-6 is the periodogram of a nonrandom train of slowly widening pulses. (Relatively little smoothing has been performed on the spectrum in Figure 2-6.) More precisely, the time series which resulted in the spectrum in Figure 2-6 may be represented by a pulse train with Period 7, the first 40 pulses being one unit wide, and the remaining 33 pulses being 3 units wide. No pulses are missing and there are no extra (noise) pulses. In terms of the signal parameters defined in Subsection 2.3, the signal here is determined by

$$T = 512; \quad D = 7; \quad d = 0.05; \quad P = 1; \quad \alpha = 0$$

Therefore, the spectrum of this signal is a set of harmonically related lines with fundamental frequency T/D = 73, as seen in Figure 2-6.

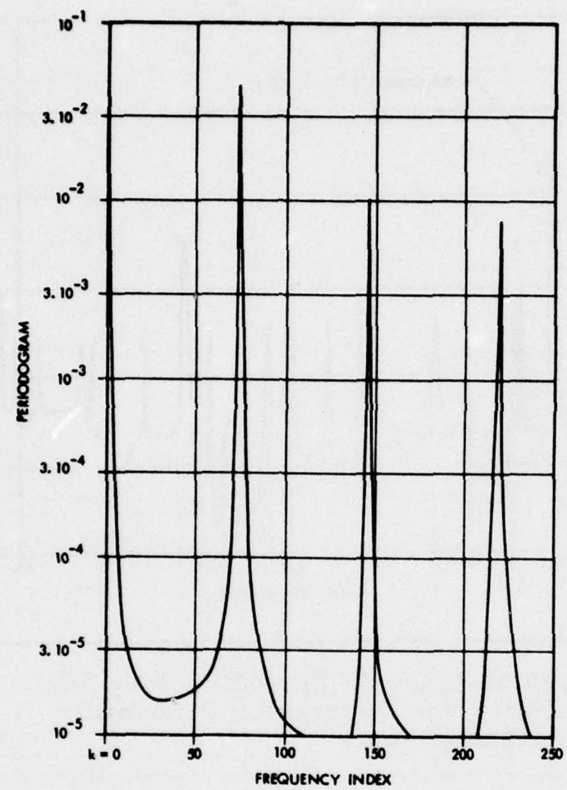


Figure 2-6. Spectrum of Periodic Train of Slowly Widening Pulses 1734-16

Figure 2-7 is a highly smoothed version of the spectrum of a random periodic train of widening pulses with a decreasing probability of pulse occurrence. Specifically,

$$T = 1024; \quad D = 10; \quad d = 0.2; \quad P = 1; \quad \alpha = 0.05$$

Therefore, the signal consists of up to 102 (nonzero) pulses, the first ten intervals in which pulses may occur are one unit wide, the second ten intervals are three units wide, etc., and the probability of pulse occurrence decreases exponentially from one with a time constant of 20. There are no extra or noise pulses in this signal, the random character of the spectrum is due entirely to the random presence or absence of signal pulses.

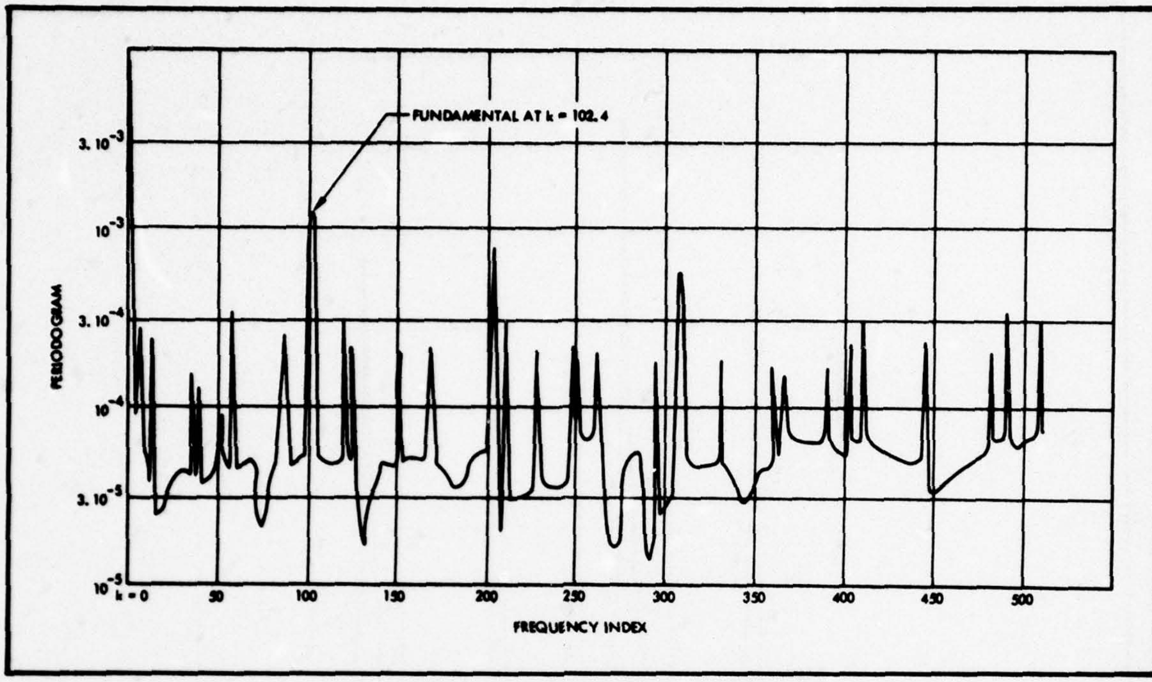


Figure 2-7. Spectrum of Random, Periodic, Widening Pulse Trains and Decreasing Probability of Pulse Occurrence 1734-17

Although no conclusions can be drawn from Figure 2-7 regarding the efficacy of spectral analysis as a technique for detecting harmonic groups, at least a partial illustration of the limitations of such techniques is given.

SECTION III

CLASSIFICATION DATA/SHIP MODELING PROGRESS

3.1 FUNCTIONAL DESCRIPTION OF A FIRST VIBRATION/RADIATION MODEL

Modeling of a main propulsion system as the principal exciter of the so-called line spectrum of acoustic radiations is well underway under the present contract effort. Objectives of the initial effort have been to identify or develop, where necessary, mathematical descriptors of the harmonic content of energy inputs, frequency response, and energy transmission characteristics of a particular ship propulsion system.

Several considerations influenced the selection of a ship for model development. The selected ship should be a relatively uncomplicated one for which detailed engineering data is available. Further, it is desirable that all data be unclassified to simplify collection and handling. The basic propulsion system should give rise to a model which can be generalized to fit naval ships of high interest.

These considerations led to the modeling of a single-screw, diesel-driven merchant ship of a design submitted to the U.S. Maritime Administration by the J.J. Henry Company, naval architects, of New York. The model of this ship can readily be modified to permit sound field syntheses of many classes of merchant ships as well as diesel-driven naval ships such as submarines, certain classes of ships; i.e., mine-sweepers, etc.

The approach taken in the vibrational/acoustic radiation modeling of ships is a conservative one. That is, ships are finite systems and considerable knowledge exists regarding the vibrational-radiative mechanisms by which their radiated sound fields are produced. The synthesis of composite models will, of course, rely heavily on this knowledge fund, some of which is based on substantial investigation and years of effort.

The engineering vibrational characteristics of ship systems in which we are most interested are those which cannot be eliminated nor reduced

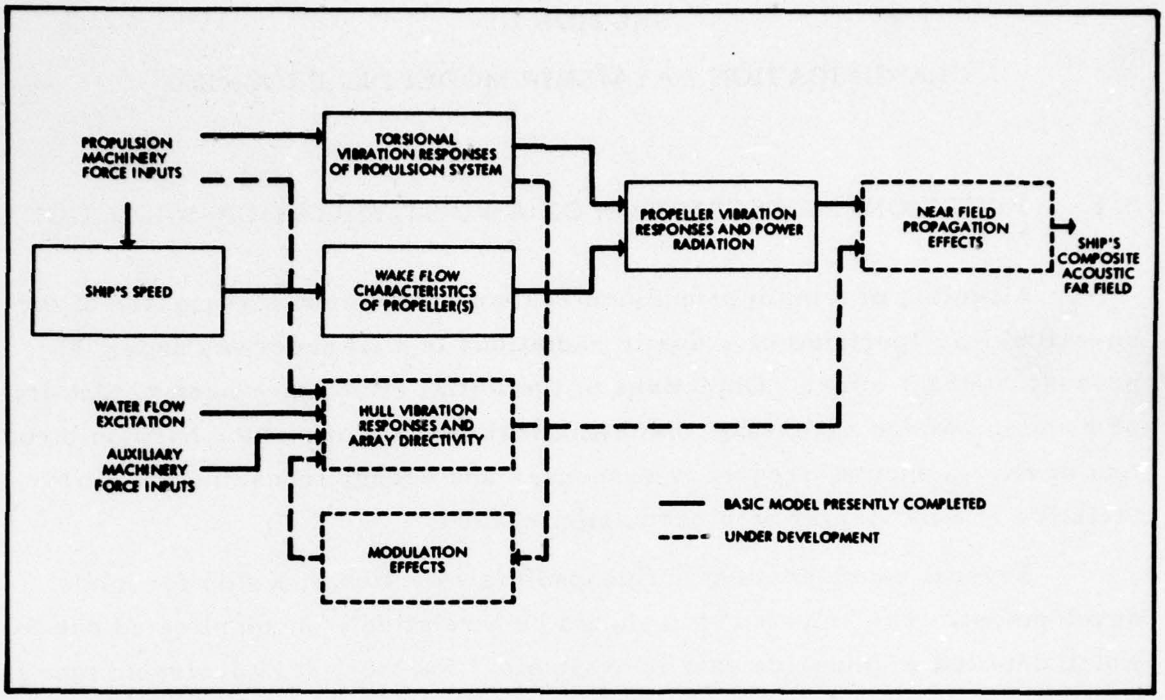


Figure 3-1. Ship's Acoustic Vibration/Radiative System Configuration 1734-6

below some level which is a function of the ship's operating power at any given time. The main propulsion system, including the engines, gearing, shafting and propellers, is the principal source of this type of excitations. Certain auxiliary machines also contribute excitations which can prove useful but these are not incorporated into the present model since their acoustic evidences are usually separable from those of the propulsion train.

3.1.1 Elements of the Problem

Evolution of a first systematic model of a ship propulsion system involved several problems which are best visualized with reference to the diagram shown in Figure 3-1. Each function included in the propulsion system line spectrum synthesizer under construction either contributes a prolific spectrum of input energies or serves as a complex frequency-sensitive filter of those excitations. The problems of developing a composite model are principally:

a. To evolve mathematical descriptors which are practically manipulable.

b. To generate outputs from each function which are compatible inputs to those which follow.

c. To account for all dispositions of energy from input to output and to retain all phase relationships through the sequence of calculations.

d. To develop plausible descriptors for vibrational/radiative mechanisms which are empirically known to be present and functional but for which mathematical descriptors are not available in literature.

e. To devise algorithms on which to base calculations for computer-programming and data manipulations in complex format, to organize the various routines into a system, to make provision for examining results at several points within the model and to present line spectra and other outputs in their most useful form.

The succeeding paragraphs discuss the nature of these problems and the means employed to date for their solution.

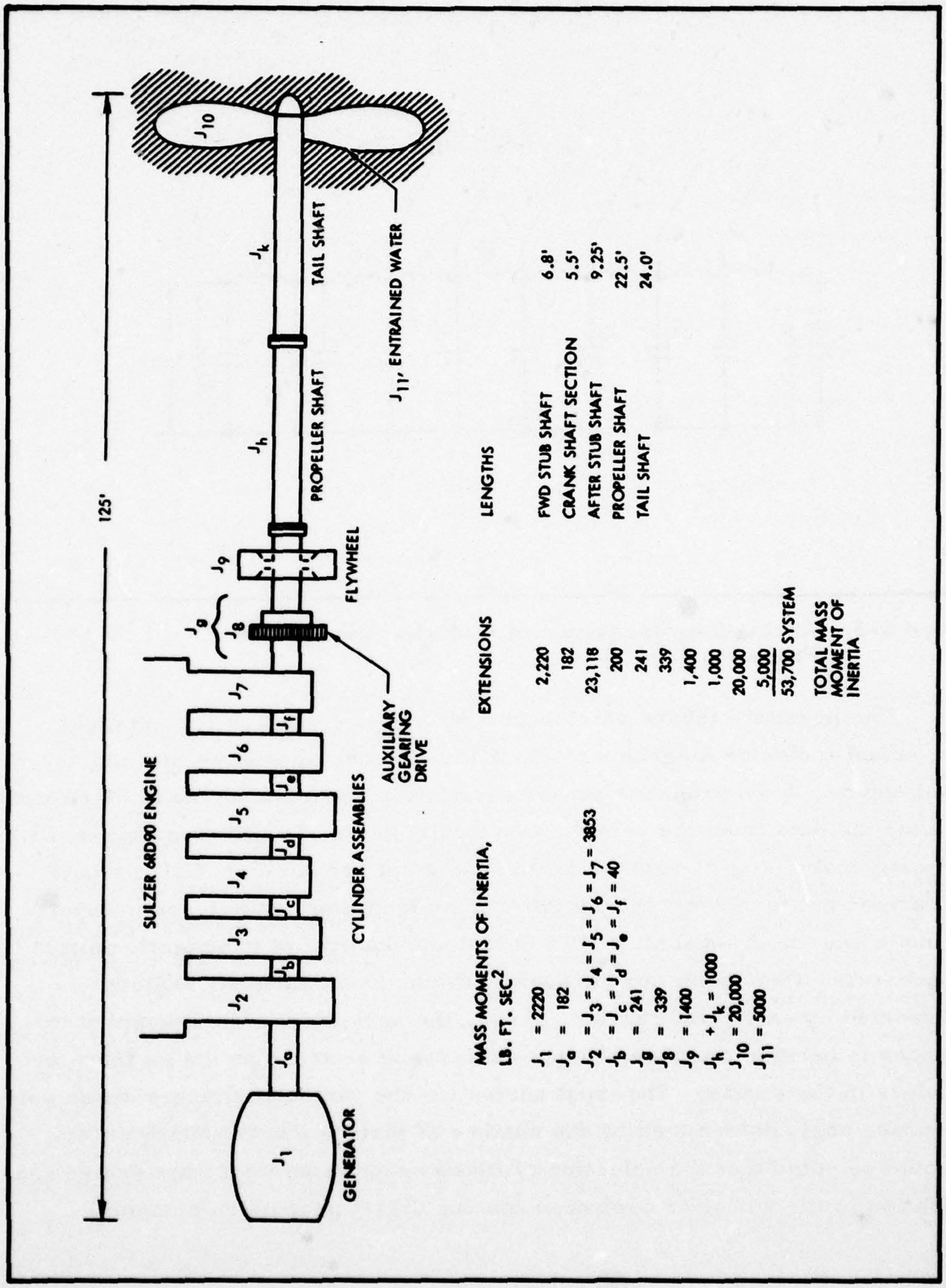
3.1.2 General Description of the Basic Model

The basic model is a computer program which synthesizes the vibrational excitation of a marine diesel propulsion system. This excitation divides its energy between two radiators; the propeller and the ship's hull. The propeller is simultaneously an influential element of the excitation system and a radiator. It is natural to expect that these two roles are interdependent and that any meaningful mathematical description of the propeller as an inertia and damper in the excitation system should be affected by its role as an acoustic projector. Thus, a model of a ship's propeller is needed which reconciles the two functions. The basic model has evolved from considerations such as these, and is derived from engineering practice in the vibration analysis of marine propulsion systems and from the need to merge diverse analytical procedures into a unified computer program.

The general nature of the model which has been developed can be described from one standpoint by stating the principle assumptions on which it is based. First, it is assumed that the propulsion system, as an exciter, can be modeled as an integral system of forcing functions, passive elements and propeller-radiator so long as radiation reaction effects at the propeller are accounted for and that similar effects from the hull do not significantly influence the characteristics of the exciting system. This does not preclude the hull excitation nor radiation. This assumption states that it is not an influential element of the excitation system. Figure 3-2 illustrates the system treated in the present model.

It is further assumed that the propulsions system can be modeled as a linear, lumped parameter, mechanical system. Linearity in this case means that the vibrational results of forcing functions applied at the individual cylinders will combine by superposition at the output. Lumping of parameters is not performed where available engineering data permits them to be described separately and where doing so will make the model more definitive and informative. The reciprocating components and the rotating components of each cylinder assembly are separated and their effects calculated. However, the compliances of coupled sections of shafting between inertias are lumped because it does not degrade the ability of the model to serve its purpose.

The mobility electromechanical analogy is taken as a useful technique for representing this propulsion system. It results in an electrical network of the form shown in Figure 3-3 representing a 9-mass, 8-compliance system with three included dampers. Dampers are, of course, the only devices by which energy can be converted or lost in a mechanical system. The most important damper in this system is the propeller which converts a steady torque (analogous to direct current) to the thrust which drives the ship and converts torsional vibrations (analogous to ac electrical power) to waves of excess pressure; i.e., to acoustic radiations. It should be noted that the network representation in Figure 3-3 is principally for convenience in setting up equations in terms which will be immediately meaningful to a majority of engineers.



1734-5

Figure 3-2. Marine Diesel Propulsion System

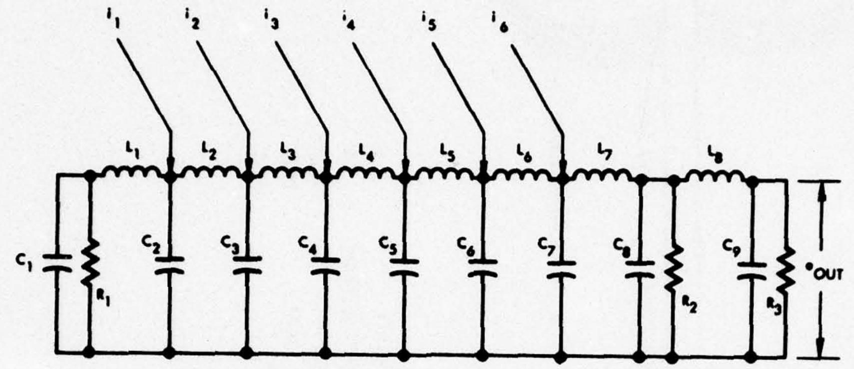


Figure 3-3. Analog Representation of a Marine Diesel Propulsion System 1734-4

The pressure inputs which occur within the cylinders are obtained from actual indicator diagrams made of the cylinder pressures of a marine diesel engine. Such pressure curves are rich in harmonics, and the form for inputting the data from the curves, as sample points, is sufficient to permit harmonic analysis up to some desired number of harmonics. Calculations are carried out to convert the sample values from input pressures to input torques along the crankshaft. This is both economical of computation effort and generates a harmonic torque series which, in the mobility analogy, is represented by electrical current. Thus, the network presents complex impedances to harmonic series of input currents at as many points as there are cylinders in the engine. The input series for the various cylinders differ only by a phase angle determined by the number of pistons and the firing order. It should be noted that the selection of firing order is an important design consideration in the vibration control of marine diesel propulsion systems.

The solution of the network for values of the input impedance it presents at each cylinder for all harmonics of input current (torque) is complicated by the fact that the magnitudes of damping in the system are functions of frequency. The impedance values must be computed separately for each running speed of the engine and, in the case of propeller damping, for each frequency of harmonic output. The initial form of output of the network is a series of voltages across the elements representing the propeller. That is, superposition of effects is assumed and phasor summation of the outputs due to each current input is made, on a harmonic-by-harmonic basis. Voltage in the mobility analogy represents velocity, a series of sinusoidal, torsional vibration velocities in the present case. To calculate power outputs the analog relationship $P = \frac{V^2}{R}$ is used, recalling that both V and R have separate values for each harmonic of output.

The development of a simple mathematical model of a propeller as an acoustic projector, which is consistent with the hydrodynamic model of a propeller, and which provides reasonably accurate predictions of signature characteristics, will be a significant and far-reaching contribution. It is believed that the results to date (through preliminary) have been significant and promising. The specific assumptions on which this part of the overall model is based are stated in the discussions of Subsection 3.1.3.

3.1.3 Functional Components of the Basic Model

Figure 3-4 is a functional flow diagram of the marine diesel propulsion system model now available for investigations of the vibrational-accoustical radiations of a specific class of ships. This diagram is also the gross flow chart of the computer-programming which implements the model. To review the functions shown in Figure 3-4:

a. Blocks I and IX read in data points taken from two harmonically rich functions. The cylinder pressure indicator curve for a particular engine is assumed common to all the cylinders of that engine. Subsequent products formed on this set of data points support an harmonic (Fourier) analysis, the results of which are an harmonic set of torque inputs to the engine. The propeller wake-inflow data used are curves for $(1 - \overline{w}_\ell)$, the weighted (from root to tip) mean longitudinal pressure wake encountered through 2π radians of

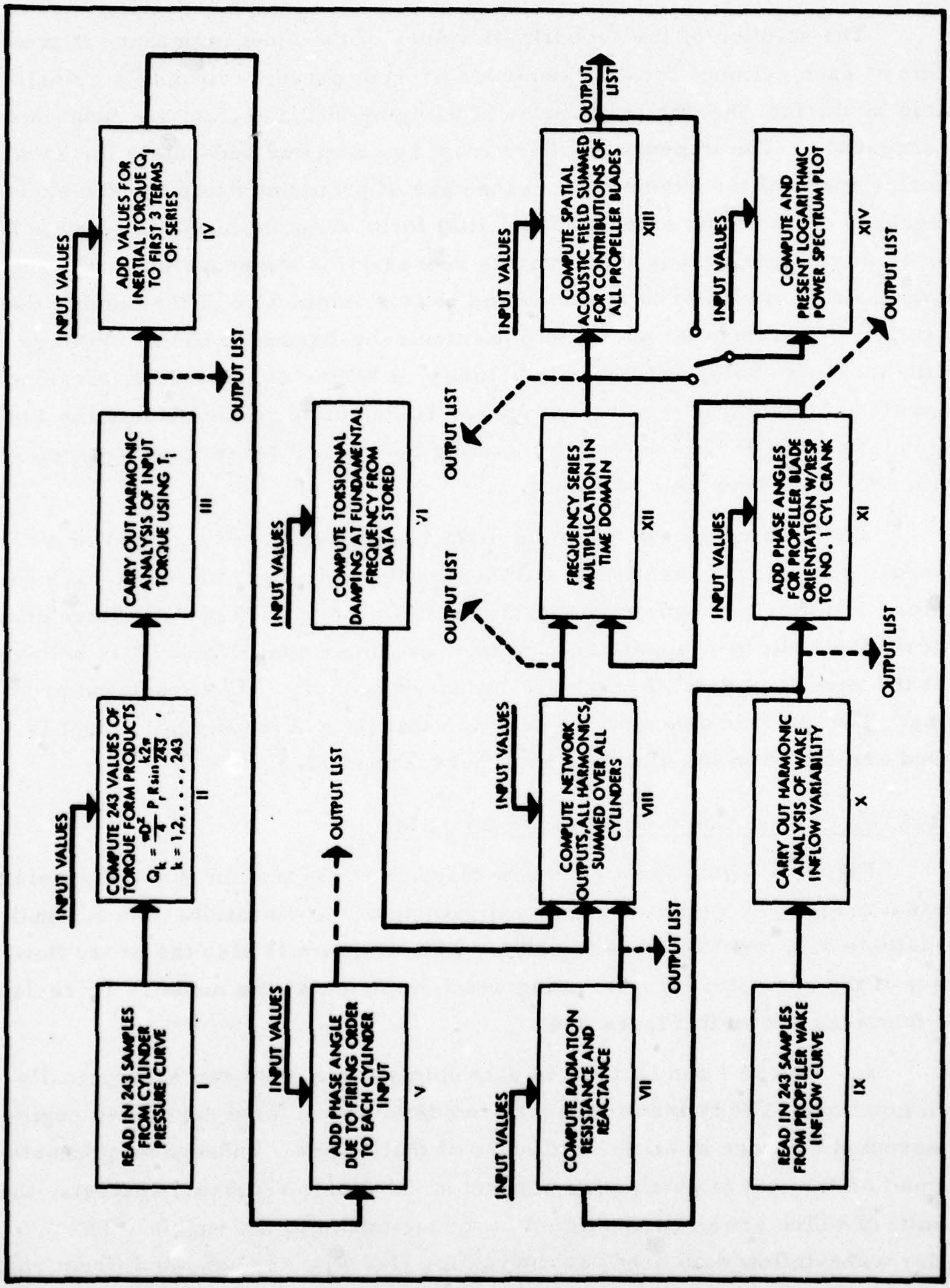


Figure 3-4. Diesel-Driven Ship Vibration/Acoustic Radiation Model Flow Diagram

1734-1

rotation by a propeller blade. (A typical curve is subsequently shown in Figure 3-6 in this report.) As many as 243 data points from each curve may be supplied the Fourier analysis routine permitting up to 121 harmonics of content to be extracted.

b. Block II converts the indicator pressure data points for a cylinder to a corresponding set of torque values at the crank. That is:

$$Q_k = \frac{\pi D^2}{4} P_k R \sin\left(\frac{2\pi k}{K}\right), \quad k = 1, 2, \ldots, K$$

where K is the number of pressure data points, D is the piston diameter, P_k are the pressure values, and R is the crank throw of the engine.

c. Blocks III and X employ the same finite Fourier analysis routine to generate the Fourier coefficients, a_n and b_n, for harmonic series of N terms, the number of harmonics of propeller shaft rotation frequency for which the program will predict vibrational and acoustical outputs.

d. Due to the varying force arm in the torque applied by a piston in a reciprocating engine as the crank rotates through 2π radians of arc, an harmonically-varying inertial torque is generated which must be added to the harmonic driving torque. Though actually an infinite harmonic series itself, the inertial torque is adequately accounted for by phasor addition of its first three terms to the series computed in Block III so long as the L/R ratio (see below) is large enough.[7] This is accomplished in Block IV. The terms added are described by:

$$Q_{inertial} = 1/2\, M_{rec}\, \omega^2 R^2 \left(\frac{R}{2L} \sin \omega t - \sin 2\omega t - \frac{3R}{2L} \sin 3\omega t\right)$$

Where M_{rec} is the mass of the reciprocating components of one piston assembly, ω is the radian frequency equal to the propeller shaft rotation frequency, R is engine crank throw as before, and L is the length of the connecting rod, usually 4 to 5 times R.

e. Blocks V and XI add phase angles to the harmonic torque series. Block V adds phase to account for the lag due to firing order of the input torques at each cylinder. Block XI accounts for the phase displacement of the propeller blades from a reference blade in rotating through the variable wake inflow. It also adds an arbitrary phase angle $\left(\text{between } \frac{0 \text{ and } 2\pi}{\text{number of blades}}\right)$ to account for the fixed difference in angular position of the reference propeller blade and the number one engine crank.

f. Block VII operates on the network representation of the propulsion system (see Figures 3-2 and 3-3). Input impedances are computed for all harmonics of input current (for reasons given in the next paragraph) at each of the input nodes (cylinder locations). Output voltages at all harmonic frequencies across the output resistance (propeller damping) are obtained by phasor summation of contributions due to the inputs from each cylinder.

The necessity for computing separate network impedances, both input and output, for all harmonic frequencies arises from the fact that the propeller functions as an acoustic projector. This is intrinsic to its function as a torque-to-thrust converter and to pertinent hydrodynamic considerations which are well developed in the literature related to propeller design and the powering of ships.[8] A unified description of the propeller as, simultaneously, a torque-to-thrust converter, as an acoustic projector, and as a variable (with frequency) damper and energy storage device has been developed for use in the present model.

g. Blocks VI and VII compute two contributions which combine to make up the all-important propeller damping and a variability (with respect to frequency) of the polar mass moment of inertia of the propeller. The viscous damping of propeller torsional vibration at a frequency equal to the propeller shaft rotation rate, which differs from the propulsive resistance to the steady-state propeller rotation, can be obtained in two ways. One, is from the usual rpm versus speed and shaft horsepower versus speed curves of the ship. Assuming power P, torque Q, and shaft speed θ given in basic units, they are related by:

$$P = Q\theta \text{ or } Q = P/\theta$$

Damping, K_o, is given by $dQ/d\theta$ so that:

$$K_o = \frac{1}{\theta}\, dP/d\theta - P/\theta^2$$

$$= \frac{1}{\theta}\left(\frac{dP}{dS}\right)\left(\frac{dS}{d\theta}\right) - \frac{P}{\theta^2} \quad \frac{\text{pounds/foot}}{\text{radians/second}}$$

where S is ship's speed in knots.

Now dP/dS and $dS/d\theta$ are just slopes which can be taken from the curves mentioned above for the appropriate ship's speed.

The second way, and one which permits accounting for variables such as propeller slip assumed constant in the preceding calculation, is through use of an extensive set of curves worked up by Archer[9] based on model experiments and empirical data. These curves yield a value for the coefficient α to be used in the equation

$$K_o = \alpha\, Q/\theta \quad \frac{\text{pounds/foot}}{\text{radians/second}}$$

The two methods yield closely similar values for K_o. Block VI is an attempt to tabulate or otherwise store in the computer Archer's data in such form that interpolations into the data for variations in propeller slip, pitch-diameter ratio and disc-area ratio can be programmed as part of the overall model.

h. The torsional vibration damping discussed in the last paragraph is applicable only to vibration at the fundamental frequency. It is well known that the damping is greater for higher harmonic frequencies. Den Hartog[10] suggests simply doubling the value of damping obtained by computing $dQ/d\theta$ previously described.

The more scientific approach is to seek a model of the propeller as an acoustic projector and to observe the results of radiation reaction on the propeller. The radiation reaction on a projector is a complex quantity, the real part of which adds to the damping and the imaginary part of which effectively adds to the mass moment of inertia of the projector.

Recalling that as a torque-to-thrust converter, a propeller imparts momentum to a column of water astern. The reaction to this action is forward momentum acquired by the ship. Thus, an ideal propeller will project water only in a direction directly opposite to that in which it is desired that the ship move. Actually, the column of water is projected somewhat downward for hydrodynamic reasons, but propeller designs in general do attempt to achieve the cylindrical column of wake immediately behind the propeller.

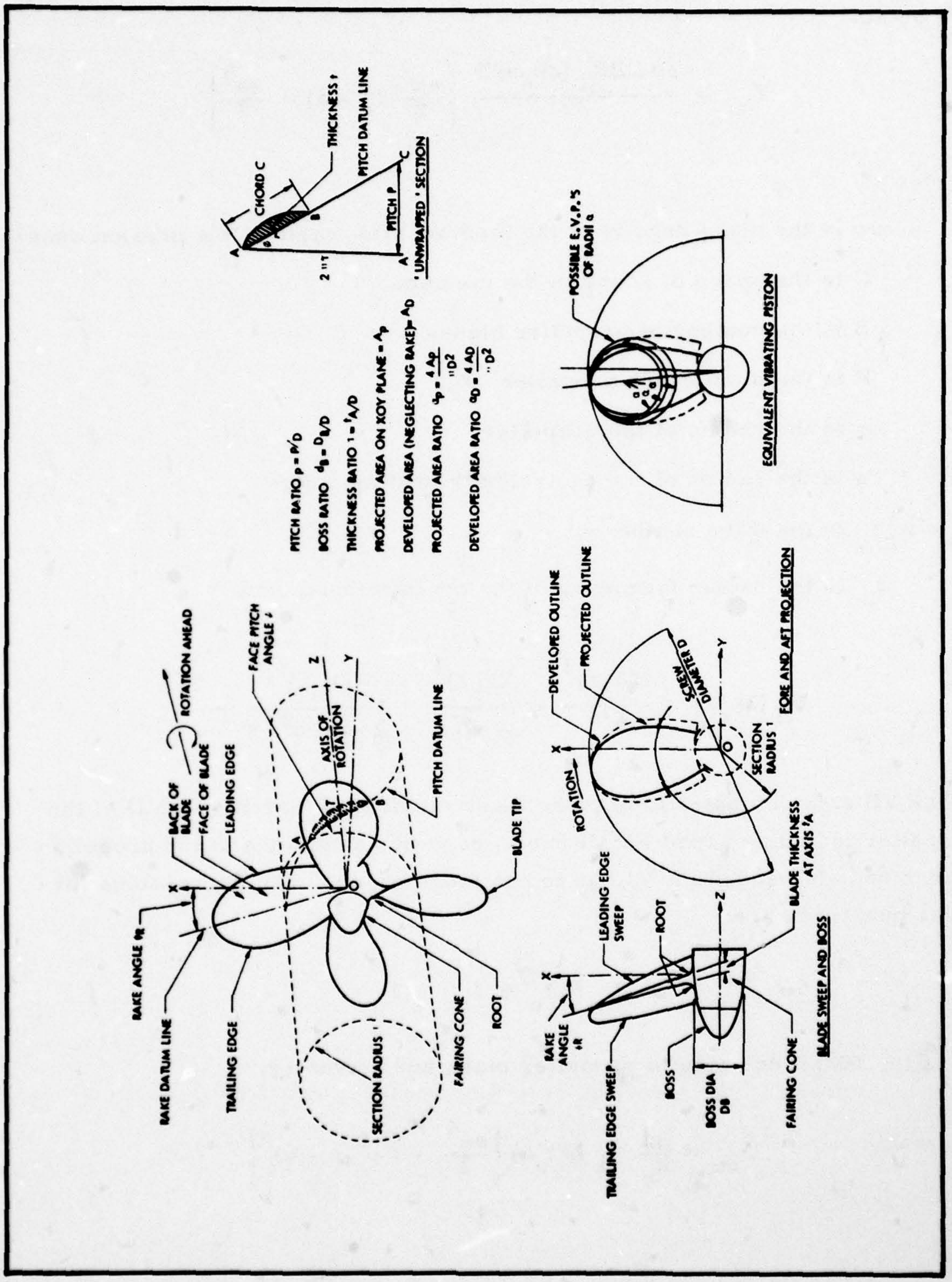
However, practical design considerations degrade the performance of a propeller. There must be a hub at the center, and the blades, near their roots, must be designed more for strength than for their efficiency in torque-to-thrust conversion. Accepting the outer two-thirds, radially, of a propeller blade as the principal region over which torsional vibrations at the hub are converted to acoustic pressure trains projected aft, a model emerges of the outer blade which is approximately equivalent to a vibrating circular piston.

This is the key assumption on which calculations of added damping and, incidentally, of added polar mass moment of inertia at the propeller in the present model are based. The propeller is then represented as an array of circular pistons as illustrated in Figure 3-5. The radius of an equivalent vibrating piston (EVP) is expected to be about one-third the route-to-tip length of a blade with the EVP tangential to the tip circle of the propeller.

Experimental data from actual ships will be needed, of course, to establish precisely what radius of circular piston will represent a blade of an actual propeller or whether a more complicated shape would improve the model, such as perhaps an ellipse. Block VII computes total damping at the propeller for each harmonic frequency,

$$K_n = K_o + K_{rn}$$

K_o was discussed in the preceding paragraph and K_{rn} is obtained by integrating for radiation damping over an EVP as described above.



1734-7

Figure 3-5. Marine Screw Propeller Detailed Parameters

We obtain

$$K_{rn} = \frac{\rho o\, CBR_1 (2k_n a) P}{2\pi} \left\{ \frac{\pi a^2}{2} (r - a) + \frac{8a^3}{3} \right\}$$

Where

ρo is the mass density of the medium (sea water in the present case)

C is the speed of sound in the medium

B is the number of propeller blades

P is the pitch of the propeller

r is the radius of the propeller

a is the radius of the equivalent vibrating piston

$k_n = \omega_{n/c}$ is the wave number

ω_n is the radian frequency of the nth harmonic, and

$$R_1 (2k_n a) = \frac{(2k_n a)^2}{2 \cdot 4} - \frac{(2k_n a)^4}{2 \cdot 4^2 \cdot 6} + \frac{(2k_n a)^6}{2 \cdot 4^2 \cdot 6^2 \cdot 8} - \cdots$$

Block VII also computes total polar mass moment of inertia (PMMI) of the propeller including added PMMI due to radiation reactance at the propeller blades and also added PMMI due to entrained water. The expressions for these quantities are:

$$J_n = J_o + J_{rn} + J_w$$

J_o is the PMMI due only to propeller mass and geometry,

$$J_{rn} = \frac{\rho o}{k_n} X_1 (2k_n a) \left\{ \frac{\pi a^4}{2} - \pi a^2 (r - a)^2 \right\}$$

where

$$X_1\,(2k_n a) = \frac{4}{\pi}\left\{\frac{2k_n a}{3} - \frac{(2k_n a)^3}{3^2 \cdot 5} + \frac{(2k_n a)}{3^2 \cdot 5^2 \cdot 7} - \ldots.\right\}$$

and

$$J_w \equiv (0.25)\,(PDR)\,J_o$$

where PDR is the propeller pitch/diameter ratio.

The series R_1 $(2k_n a)$ and X_1 $(2k_n a)$ are the piston resistance function and piston reactance function originally derived by Lord Rayleigh and described in his "Theory of Sound."

i. Block XII combines the torsional vibration excitation transmitted via the propeller shaft to all blades with the harmonic wake inflow pressure variations experienced by each blade as it rotates through 2π radians of arc. This becomes a polynomial multiplication of the torsional vibration series, analogous to output voltages in our network representation, with the harmonic wake series which, it will be shown, is equivalent to harmonic variation of the value of the network output resistance.

It is evident that harmonic analysis of a mean longitudinal wake curve, as illustrated in Figure 3-6, will yield a constant term which is the average value of the curve over the 2π radians for which it is plotted. This could be expressed as

$$\overline{(1 - w_\ell)}$$

where

$$(1 - \overline{w}_\ell) = \overline{(1 - \overline{w}_\ell)} + \sum_{n=1}^{N} \text{(sinusoidal components up to N harmonics).}$$

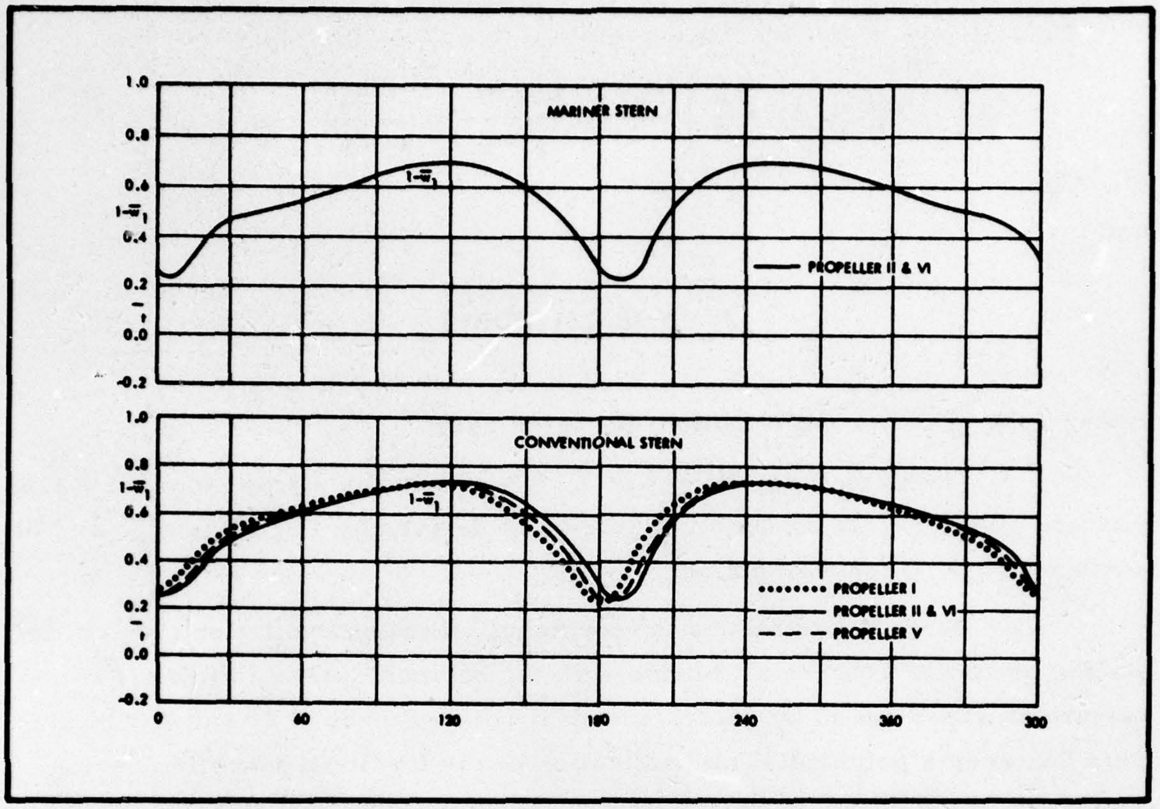


Figure 3-6. Mean Longitudinal Wake Inflow and Tangential Wake Curves 1734-3

Repeating the equations for propeller damping at these harmonic frequencies, we have

$$K_n = K_o + K_{rn}$$

and

$$K_{rn} = \frac{\rho \sigma C B R_1 (2k_n a) P}{2\pi} \left\{ \frac{\pi a^2}{2} (r - a) + \frac{8a^3}{3} \right\}$$

The factor P, propeller pitch, as normally used, is a constant-valued statement of a design characteristic which is the advance to be expected in one revolution of the propeller in the absence of any slip. However,

there always is slip; i.e., failure to advance the design distance per revolution. The generally accepted view is that due to the mass of a ship, the slip in response to propeller torsional vibrations is a function of frequency but not of time under steady-state operating conditions, and its value approaches 100 percent at high frequencies. Slip, S, pitch, and wake inflow are related by the expression

$$P = \frac{V_s (1 - \overline{w}_\ell)}{\theta(1 - S)}$$

where V_s is the ship's speed and θ is the shaft rotation state.

Thus, the factor P as used in the expression for K_{rn} should not be thought of as the constant but rather the ratio on the right whose numerator includes the wake inflow variability with time and the denominator of which includes the variability with frequency due to slip. It is especially significant to regard slip in the above expression as an element of the factor $\frac{1}{(1 - S)}$. As slip approaches 100 percent this factor should become asymptotic to a very large number. In order to use a constant value for P in the expression for radiation damping (assuming constant V_s and θ), the variabilities of $(1 - \overline{w}_\ell)$ and $\frac{1}{(1 - S)}$ must be separately accounted for. Upon closer examination, it appears that the quantity $R_1 (2k_n a)$ describes a variability with frequency quite similar to that expected of $1/(1 - S)$ and for much the same physical reasons. Plots of $R_1 (2k_n a)$ and $X_1 (2k_n a)$, normalized by the variable $2k_n a$, are presented in Figure 3-7. This leaves only the variability of $(1 - \overline{w}_\ell)$ unexpressed in K_{rn} as it stands. This variability is described by the harmonic series which resulted from Fourier analysis of the wake inflow curve, which, in effect, results in varying time and frequency damping. The reason for frequency series multiplication in Block XII becomes clear. Damping, in the mobility analogy, is the inverse resistance or conductance. The analog voltage (vibrational velocity) across the conductance from Block VIII has already been obtained. Output current is now the product of voltage and conductance. Having voltage and current, output power is readily computed.

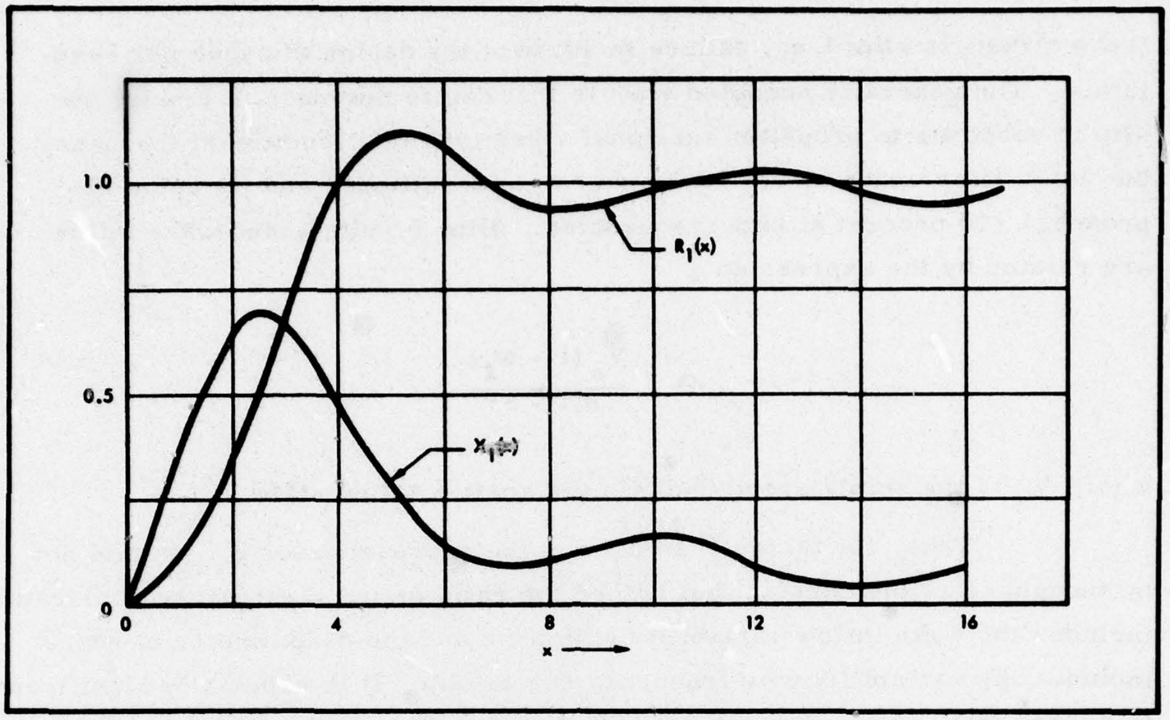


Figure 3-7. Piston Radiation Reaction Functions 1734-2

It should be noted that the frequency series multiplication is of two complex polynomials which in the present model may have up to 121 terms each. Their product will consist of 2N-1 terms, or as many as 241. Each product term, in turn, resolves, using trigonometric identities, into two terms one at the sum and one at the difference of the two frequencies entering into the particular product term. Only sum and difference terms at frequencies not higher than those of the two input series are preserved. That is, only the first 121 of the 241 terms resulting from the multiplication are regarded as useful because significant contributions to terms 122 through 241 could be expected which are not generated by this multiplication.

j. The mathematics and computer algorithms for Block XII have not yet been developed. For the present, a simple rms summation of the output power computed for each blade of the propeller is performed. This power is expressed in watts for each harmonic frequency up to the 121st harmonic of a fundamental at the frequency of propeller shaft rotation.

k. Block XIV, now being set up, will yield an output magnetic tape which can be taken to a CALCOMP plotter. This will in turn generate plots of output power spectra resembling those of Figures 3-8, 3-9 and 3-10. The vertical scale will be acoustic output power in dB relative to 10^{-7} watts.

3.2 EXERCISING OF THE BASIC MODEL

The two purposes of exercising the first model are to gain insights into the vibrational behavior of the ship it represents and to perfect the model as an investigative tool. As stated earlier, the basic model which is presently being used is of the central excitation system which leads a ship to radiate its so-called line spectrum of propulsion-associated frequencies. Whereas the effort to date synthesizes the principal excitation, work remains to be accomplished in describing the composite sound field. It is important, however, that the excitation mechanism be thoroughly understood as the hull array and the combining with the propeller and hull radiations in the near field are described.

The term "exercising the model" is used to represent the procedure of varying parameters within the program mathematics to observe the effects particular parameters have on the output power spectral density. In the case of parameters which can be varied independently, exercising consists of stepping those segments of the computer program in which the parameter operates through solutions of their functions through some range of parameter values. To date the model has been exercised by introducing data points for three different wake-inflow curves into the program. These are the $(1 - \bar{w}_{\ell})$ curves in Figure 3-6 for: (1) the Mariner stern, Propellers II and VI, (2) the conventional stern, Propellers II and VI, and (3) conventional stern, Propeller I. The power spectral output differences corresponding to these differences in the basic ship are seen in the plots of Figures 3-8, 3-9 and 3-10, respectively.

It is evident that exercises, such as those described above, involve large-scale substitutions of data and may call for special-purpose computer routines to analyze the effects. A routine is being written which will subtract a trend from the whole set of spectral outputs and perform a harmonic analysis on the residuals to ascertain the extent of harmonic groupings within the output spectrum.

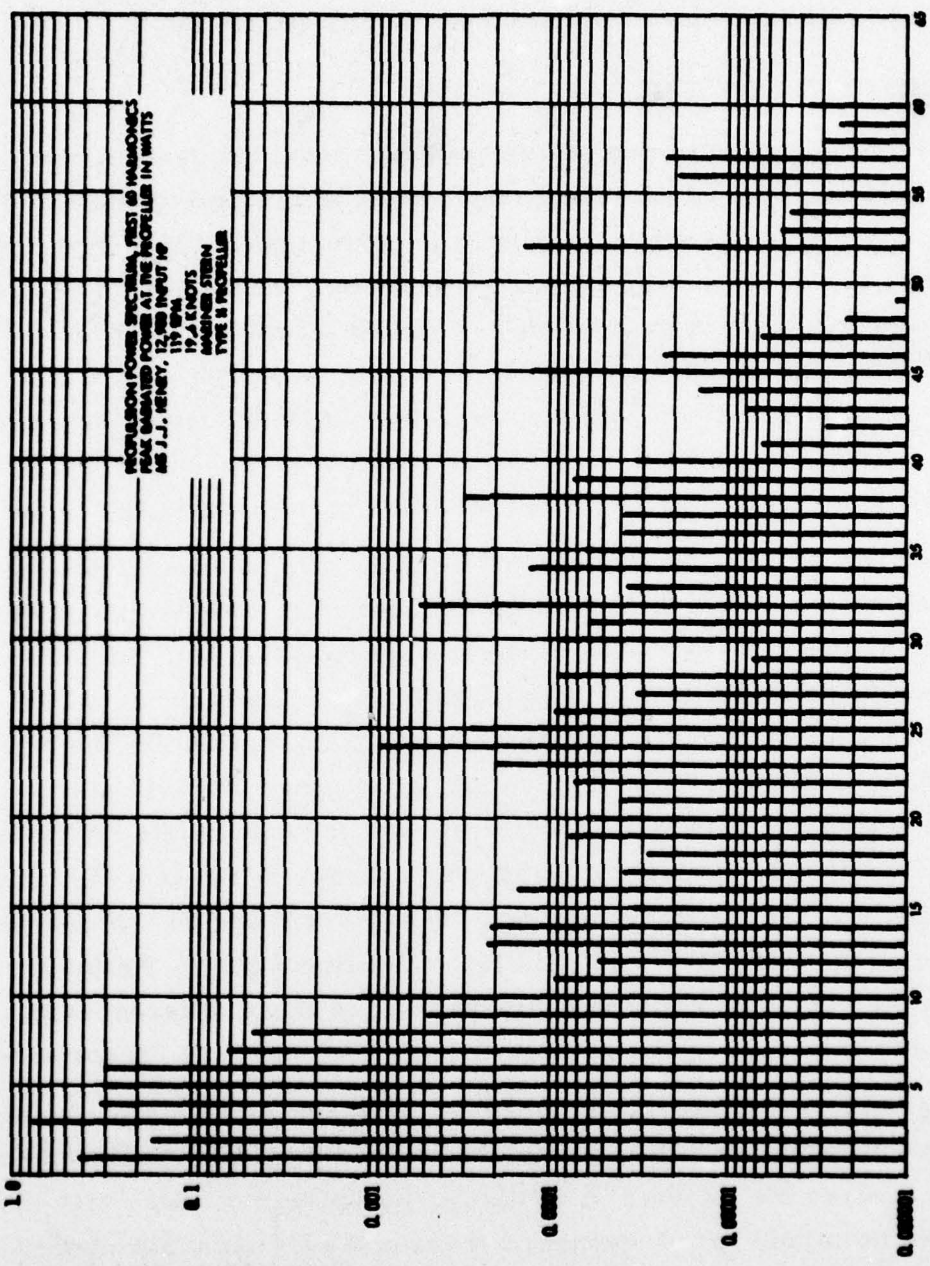
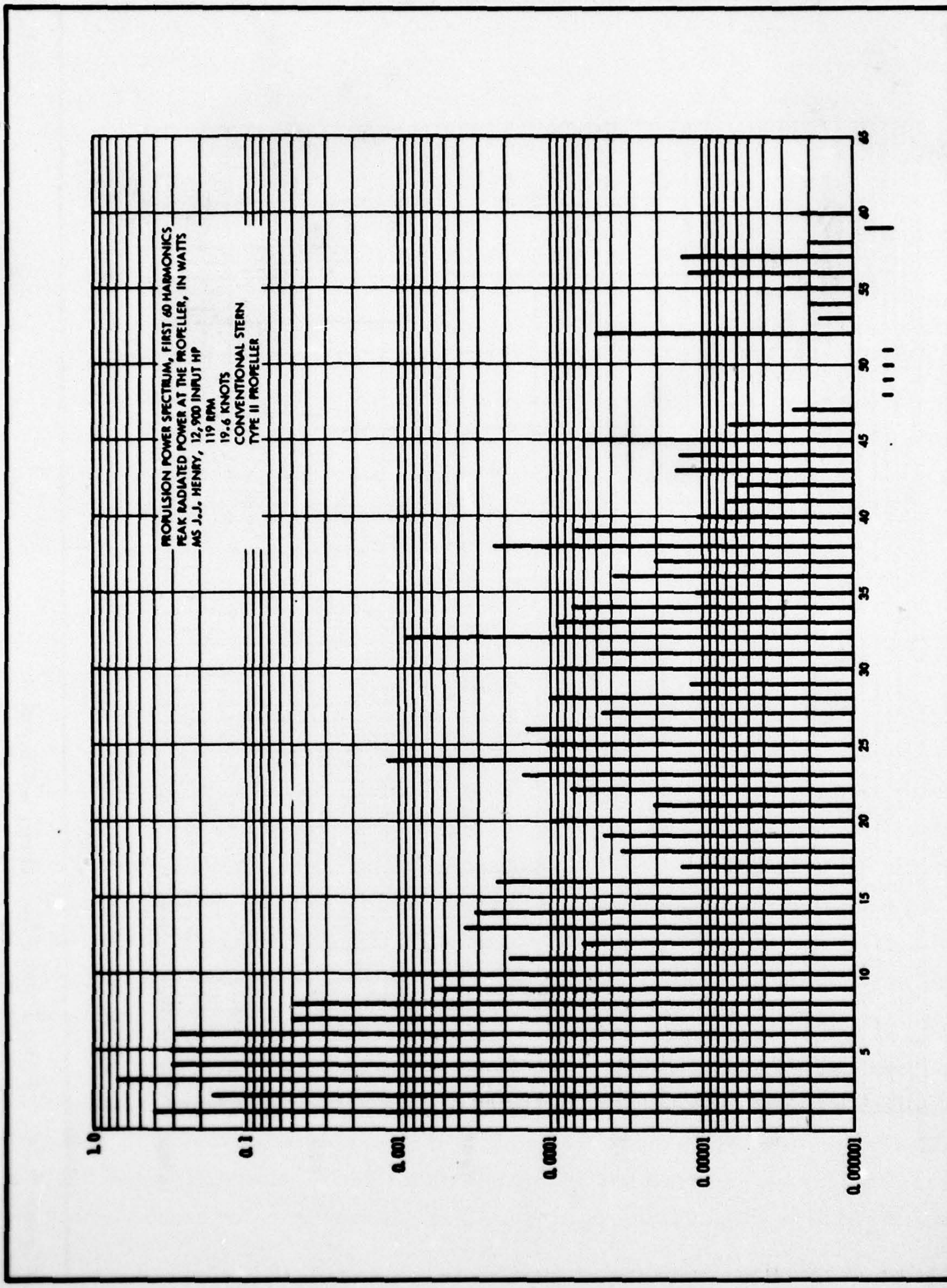


Figure 3-8. Peak Power Spectrum – Output 1

1734-8



1734-9

Figure 3-9. Peak Power Spectrum – Output 2

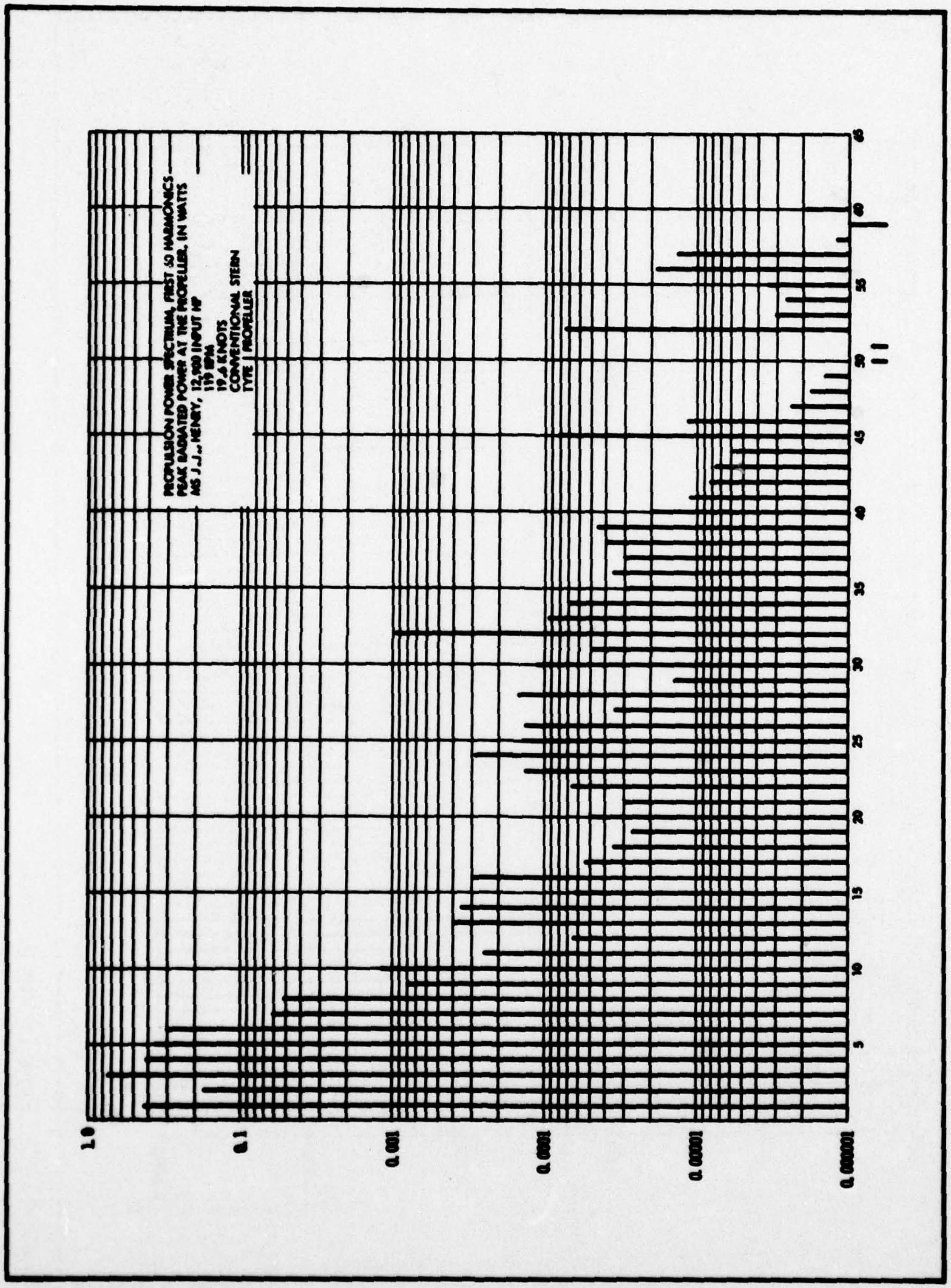


Figure 3-10. Peak Power Spectrum — Output 3

1734-10

Exercises of interest to be carried out using the present basic model may be grouped into two categories, and at least two analyses requiring their own computer routines can be listed.

a. Exercises to examine effects of varying parameters peculiar to diesel drives

(1) Changes of cylinder firing order

(2) Changes in distribution of damping over the length of the drive train

(3) Changes of ship's speed within a range normal for the ship

(4) Variation of polar mass moments of inertia of fly wheel, integral and gear-driven auxiliaries

(5) Attachment of devices such as a Bibby detuner to the engine

(6) Variation of fixed phase difference between engine crank and propeller blades

(7) Variation of engine crank-throw to length of connecting rod ratio, R/L

b. Exercises to examine effects of varying parameters common to propellers and ships in general

(1) Differences in configuration of stern structure

(2) Differences in propeller design, including number of blades

(3) Differences in ship loading and resistance due to wind, sea state, etc., as reflected in change of propeller slip

(4) Variations, within ranges consistent with resistance-powering considerations, of propeller pitch-diameter ratio and disc-area ratio

(5) Variation of assumptions relating an equivalent vibrating piston to actual configuration of a propeller blade

c. Analyses utilizing computer routines

(1) Holzer method analysis to determine the natural resonances and filter characteristics of the entire propulsion system

(2) CEPSTRUM-like analysis of the predicted ship's power spectrum outputs to find relatively invariant harmonic groupings useful for passive sonar classification purposes

3.3 ACQUISITION OF MONITORED DATA AND ENGINEERING DATA IN PREPARATION FOR MODELING ACTUAL SHIPS

Preliminary efforts have been made to organize the assembly and collection of monitored ships' sound data. A substantial amount of instrumentation quality recordings of ships' radiated sound taken under controlled conditions will be required to verify the computer simulations generated through the modeling technique. All of the inherent problems of acquiring good underwater acoustic data prevail here.

At the same time, more than one promising source of good data exists and has been made available to Litton. There remains primarily the problem of exploiting these sources, which will require that time and a continuing attention to detail be devoted to this aspect of the work.

As a result of ship monitoring runs carried out by the Navy's Acoustic Pressure Check Range (APCR), Fort Story, Virginia, tape recorded data are in hand for three U. S. Navy ships:

a. USS Raleigh (LPD 1)

b. USS Carp (SS 338)

c. USS Eaton (DD 510)

Data for nine merchant types were gathered, namely:

a. MS Vishva Shanti (oil engine)

b. SS Drepanon (reciprocating steam)

c. SS Queensville (geared turbines)

d. Copiapo (geared turbines)

e. MS Kerkedyk (oil engine)

f. SS Shell Naiguata (geared turbines)

g. MS Hickory Knoll (oil engine)

h. SS Cosmopolitan (turbo-electric)

i. MS Athelbeach (oil engine)

Three of the ships listed above were visited for purposes of obtaining detailed engineering data. These were Queensville, Cosmopolitan and Athelbeach. Litton observers were present while these ships were being monitored and the Litton observers considered the runs to be sufficiently free of interference to be potentially useful. Since then, however, the taped data have been submitted to STIC for spectrum analysis. It appears that the tape recorder at APCR introduced such intense artifacts at 60 cps and harmonics of it that the data may not be useful. However, this remains to be investigated.

Because the next step in developing the ship vibration modeling/sound field synthesis capability is to apply it to an actual ship on which recorded sound data is available, the SS Athelbeach will be modeled. Excellent engineering data were obtained from the visit to the ship, and additional data which will support a more accurate model are being requested of the ship's builder, Hawthorne Leslie, Ltd., of Newcastle on Tyne, England. The ship's engineering plant consists of an oil engine (slow speed, two-cycle diesel) and direct drive. The model can be set up using straightforward modifications of the basic model which is presently being exercised.

SECTION IV

PLANS FOR FUTURE EFFORT

During the next quarter, effort will be directed toward processing recorded ship sounds, continued testing of processing methods on simulated signals, an analytical study of the important problem of harmonic group detection, collection of additional recordings and data as required, and a continuation of modeling the mechanisms of ship sound generation.

In particular, it will be possible to determine the need for additional data and sound recordings only after analysis of the initially collected recordings. For example, it is not clear that the recordings collected at Fort Story are adequate for a realistic study of signal processing problems. Furthermore, it is desirable that several examples of signals of significant military interest be examined.

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